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SOME NOTES ON THE P-GEM

by

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Approved by:

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FOREWORD

The Princeton twenty-foot ground effect machine, first operated in October 1959, has recently been modified to include a 180 HP Lycoming engine replacing the former 43 HP Nelson engine. During the past several months the machine has undergone certain trials while plans and instrumentation were being prepared for the second major flight test program. As a result of these trials, observations have been made that are interesting not only to the writers but to many of our visitors active in the field of ground effect research. While the Princeton group, as with most research teams, normally leans toward quantitative results to describe a phenomenon under investigation, we feel in this case that a qualitative paper is indicated as an interim report.

It is our hope that this paper will to some extent point up one of the values of a research machine such as the P-GEM in that certain operational problems may be more rationally predicted for the more sophisticated machines now under development in many quarters.

Princeton research in this field is under the sponsorship of the U. S. Army, TRECOM and under the direction of Professor C. D. Perkins of Princeton University.

SUMMARY

Certain observations are reported in a qualitative manner regarding operational and other flight experiences with the Princeton 20 ft. Ground Effect Machine. Comments on the fan-inlet problem, stability and stabilizing devices, and operations over land, water and snow are made as a result of many hours of operation of the P-GEM. Tentative conclusions are drawn which largely reflect the authors' opinions as influenced by the observations.

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I. INTRODUCTION

The many parameters that have been devised to completely describe the behaviour and acceptability of an aircraft frequently fall short of telling the entire story. While it is not suggested that all significant quantitative data have been acquired on the P-GEM, or any other manned GEM for that matter, certain qualitative observations have been made which indicate the probable magnitude of some operational problems. Also, and of equal value, these observations help point the way to the solutions of the problems so far encountered.

The P-GEM as originally built was powered by a 43 HP Nelson engine. A brief flight test program was conducted and reported upon early in 1960 (Reference 1). It seemed evident that the performance of the machine was not sufficient to permit significant flight research; therefore, it was decided to install additional power. The usual vicious circle resulted. Because of the additional weight and power of the new engine, additional structure, fuel and ballast were required. In addition, the original electric servo controls were changed to a direct mechanical system and strengthened for the new higher jet velocities.

The results, however, have been rewarding. Even though there has been a 50% increase in gross weight, performance has substantially improved and our capability of conducting significant flight experiments has been vastly enhanced. Later sections of this paper will define this new performance in more detail.

While this report deals largely with the modified P-GEM, two experiments made with the 43 HP version subsequent to the publication of Reference 1 will be discussed.

II. DISCUSSION

Figure 1 shows the original P-GEM and the modified version of the machine. The major external differences are an enlargement of the inlet duct from four feet to five feet in diameter, the installation of a four-bladed fan designed to absorb 180 HP, the addition of external fuel tanks, and the raising of the cockpit canopy four inches. Fuel tanks were placed outboard to avoid further deterioration of internal efficiency, and considerable electronic gear associated with the former servo control system were removed from the interior of the machine for the same reason. Otherwise there has been no change in the internal aerodynamics of the machine.

Prior to the installation of the larger engine, an internal efficiency $({}^{P}T_j/{}^{P}T_j)$ was estimated to be between 45 and 50%. It was realized that a great improvement in performance could be effected by the addition of more sophisticated internal ducting. It was decided, however, that the desired performance could be achieved more expediently by adding power rather than by removing power losses. This decision would have been intolerable for an operational machine; however, it is justifiable in an experimental craft intended primarily to investigate control and static and dynamic stability. It is conceded that the present capability of the P-GEM could be achieved with substantially less installed horsepower if the rather poor internal aerodynamics were improved.

A. The Fan - Inlet Problem

The first fans designed for the 43 HP P-GEM were designed to load the Nelson engine to a full throttle sea level condition to 4000 RPM. The fact that this did not occur, even after a systematic increase in root blade angle, led to a re-examination of the design assumptions. It was originally assumed that the inflow velocity would be uniform and parallel, although it was recognized even then that the shape of the inlet would undoubtly influence the distribution to some extent. In order to converge more rapidly on the "correct" fan for the machine, the inlet was very carefully probed with both static and total pressure tubes. This experiment revealed that, far from being uniform and parallel in nature, the in-flow was in fact varying across the inlet in a parabolic fashion. Figure 2 shows this velocity distribution and how the duct seemingly influences the in-flow field. The effect of this parabolic distribution on the fan designed for a uniform in-flow velocity was to reduce the fan tip angle of attack to approximately 0° for the greatest fan root angle tested. There is, therefore, little wonder that fan efficiencies were of the order of 45% for the best of this first series of fans.

The results of this fan-inlet study were incorporated into the design of the fan for the 180 HP engine. It appears from the RPM/manifold pressure relationship in the modified P-GEM that we are still significantly far from the "correct fan"; however, a rapid convergence on the solution of the problem has been made. In this respect it is desired to point out that an extensive study of the literature dealing with ducted fans indicates work yet to be done in this area of fans operating very near a faired inlet. Of most significance is the work done at Mississippi State College under the direction of the late Dr. August Raspet (Reference 2).

The estimated effect of the new inlet on the inflow distribution in the modified machine produced a fan design with zero blade twist and a blade angle of $\beta = 17^{\circ}$. This fan was designed to absorb 180 HP at 2900 RPM and 28.5" Hg. manifold pressure. But it has been observed in operation that with the radial stabilizing slots closed (see Figure 3), the maximum manifold pressure at 2900 RPM is approximately 24.5"Hg. This represents a brake horsepower absorption of 150 HP. With the radial slots open, however, the manifold pressure at 2900 RPM is approximately 26.5" Hg. indicating a horsepower absorption of 169 HP. This may be a function of the mass flow change as internal total pressure drop is changed by opening additional slots. This would directly change the fan blade angle of attack and $^{L}/_{D}$ of the blade section. In any event it is seen that the fan needs modification to fully utilize the installed horsepower. Experiments presently are being designed to determine the precise operating conditions of the fan for various conditions of RPM and stabilizing slot opening.

B. <u>Comments on Performance and Stability</u>

The 43 HP version of the P-GEM was finally capable of approximately 12 inches of ground clearance and had, at that altitude, approximately neutral static stability in the hovering condition. The gross weight was about 1100 lbs.

The modified P-GEM with full fuel load has a gross weight of 1600 lbs. and a maximum hovering altitude of approximately two feet with the stabilizing slots closed. Under the condition of minimum fuel load the gross weight is approximately 1450 lbs. and the maximum hovering altitude appears to be between two and two and a half feet, again with the stabilizing slots closed. In both of these conditions, however, the machine is statically unstable. Tests with the radial stabilizing slots open showed the machine to be positively stable at full throttle to the extent that it was possible for the pilot to hover "hands-off" the controls. With an intermediate fuel load the maximum hovering altitude appeared to be no more than approximately eighteen inches, with stabilizing slots open, which certainly appears to be a high cost in hovering performance to achieve inherent static stability.

An interesting observation with the radial slots closed was that at full throttle, even though the machine was unstable in hovering, its response to a disturbance was such that the pilot could manage to keep a level attitude. This means that the rate of response to an external disturbance was low enough for the pilot, by working very hard, to act as a rather effective stabilizer. It must be said, though, that on occasion the pilot gets in phase with the disturbance with the result that one edge of the machine will lightly touch the ground.

It has also been observed that the static instability appears to vanish in forward flight. In this respect it should be remembered that the P-GEM in forward flight is in a marked nose down attitude so that a slight loss in average height or the angle itself might be influencing this apparent stability. Experiments are being planned to shed additional light on this rather favorable characteristic.

Regarding maximum speed: the P-GEM develops horizontal forces by tilting in the appropriate direction. Thrust is somewhat enhanced by the tail rotor which produces an additional 15 to 20 lbs. of static thrust, although the main function of this rotor is to produce torque about the normal axis for directional control. The 43 HP version of the machine, which could produce an average ground clearance of 10 to 12 inches when tilted, had a maximum speed on level ground in a zero wind condition of approximately 23 m.p.h. The 180 HP version of the craft has an average ground clearance of 20 to 24 inches and consequently can be inclined to a much greater angle. But it has a maximum airspeed of only 26 to 27 m.p.h. While this performance might at first glance appear to be discouraging, it was by no means unexpected. Since the machine has greater thrust at the greater negative angles of attack, the lack of a substantial increase in maximum speed must obviously be due to additional drag. It is reasonable to expect that there is an increase in drag due to a change in α; however, it is also clear that there is a much greater momentum drag at the higher ground clearances since the augmentation ratio is greatly reduced. This case can be easily argued by referring to Figure 4 and by the following relationships:

Momentum drag can be expressed as

mV across the boundaries 1 and 2

or $$D_M = mV \quad \text{-----------------------} (1)$$

Considering the relationship

$$A = \frac{L}{mv_j} \quad \text{or} \quad L = A\, mv_j \quad \text{----------} (2)$$

the ratio L/D_M becomes

$$L/D_M = A \frac{v_j}{V} \quad \text{-------------------} (3)$$

or for the general case for zero momentum recovery, or

$$L/D_M = A\, {}^{v}j/V \; (1-\eta) \quad \text{-----------} (4)$$

where η is the momentum recovery factor.

C. Over Water Characteristics of P-GEM

Early in 1960, over water trials were conducted with the 43 HP P-GEM with most interesting results. The water area, a farmer's pond of several acres located near the Forrestal Research Center in Princeton, was at the time perhaps two to three feet deep in the center gradually shallowing to the banks. The surface conditions were quite calm displaying only the slight chop due to a 12 kt. wind.

The first of several encouraging observations was that the water spray due to the jet efflux was minimal and did not seem to exceed two feet in height. No spray was ingested in either the hovering or forward flight case (see Figure 5), and the spray presented no visibility problems to the pilot even though the cockpit canopy is very close to the periphery of the machine. It should be emphasized, however, that the reason for this lack of a water spray problem is the relatively low jet velocities. The average dynamic pressure in the nozzle was approximately 3.5 lbs. / ft.^{2}. This is a good confirmation of NASA, Langley, findings that dynamic pressures below 5.0 lbs. / ft.^{2} should present no spray problems.

The second interesting observation was that the machine was capable of landing and rising from the water surface with the same ease and lack of problems associated with this operation over land. It was further observed that the P-GEM seemed to hover slightly higher over water than over land at the same power setting. If this impression is correct, it is not completely clear why it is so. One plausible explanation is that the presence of the peripheral water spray, even though light, serves as a hydro-curtain or skirt to retard the escape of the jet efflux.

In the forward flight regime over water it was found that maneuvering (turning) was enhanced by banking the inside edge of the machine until this portion of the craft was into the water enough to serve as an effective keel. By this means much tighter turns could be made over water than over land due to the additional side force available to resist skidding out. From film records of these trials it has been observed that a bow wave was created in forward flight over the shallower portion of the pond but this was not noticed over the deeper water. It is not certain, though, that the bow wave was not caused by the nose of the P-GEM dipping into the water on the occasion of the observation.

D. <u>Over Snow Characteristics of P-GEM</u>

The 43 HP version of the P-GEM was tried, on one occasion, over fresh snow early in 1960. During the heavy snows of the winter of

1960-61 the 180 HP P-GEM has been repeatedly tested over both new and old snow.

The most conclusive observation made was that there are many different conditions of snow and that these are constantly varying - also that the P-GEM behaved differently over each of these varying snow conditions. It is not possible to accurately report behaviour of the craft as a function of snow condition since the authors are incapable of classifying snow, but within this limitation the following observation is considered generally correct: the two extremes of snow conditions are on one hand a dry powdery surface and on the other a heavily crusted surface. As one might guess, GEM operation over the former produces quite a snow cloud - the magnitude of which is probably dependent upon jet velocities. But it has been observed that operation of the P-GEM over a lightly crusted snow produces little or no snow cloud unless a landing wheel or the periphery of the machine breaks the crust, which then does result in a cloud.

These two extremes produce relatively minor operational difficulties. By far the most troublesome is an intermediate wet snow condition. It has been found that operations over this type of surface can be carried out successfully as long as forward speed is maintained. At approximately 25 m.p.h. the P-GEM manages to outrun the snow cloud to the degree that the forward one third of the machine is clear while the remainder of the machine is completely invisible in the cloud. At these speeds the blowing snow does not seem to adhere to the surface of the machine. However, in hovering flight the recirculating wet snow rapidly builds up on the upper surface of the craft. In the case of the P-GEM with its light base loading, this build-up of wet snow in the hovering state was sufficient to almost ground the machine within a time period of approximately two minutes. This, of course, was due to the weight of snow taken aboard.

An interesting characteristic of the P-GEM and presumably, to a greater or lesser degree, of all ground effect machines is the ability to jump over obstacles slightly higher than the maximum hovering height of the machine. This has been observed in driving the machine from a cleared ramp onto a snow covered field with a mound of snow (from a snow plow) separating the two areas. Figure 6 shows diagramatically the technique used in hopping the P-GEM over a snow bank several inches higher than the hovering height of the machine for any given weight condition. It will be observed (Figure 6-a) that the machine in hovering flight at two lengths from the snow bank had approximately two feet of ground clearance. Figure 6-b shows the P-GEM in an attitude of maximum acceleration, while Figure 6-c shows the sharp pull up required for the nose wheel to clear the mound. Finally, Figure 6-d shows the machine in forward flight having passed the snow bank without scraping the surface.

It seems evident that the width of the mound contributed greatly to the machine's ability to make the jump since the very presence of the broad obstacle beneath the base helped lift the craft without physical contact. However, it is not suggested that this maneuver would enable the P-GEM to clear successfully a rail fence of the height of the snow mound.

III. CONCLUDING REMARKS

From the foregoing description of the several operational characteristics of the P-GEM, certain tentative conclusions can be drawn:

a) The combined fan-inlet problem is one requiring more work to approach the fan efficiencies which are theoretically possible. Closely associated with this problem is the matter of the over-all internal aerodynamics of a GEM, which to date has not received all of the attention which will be required in order to produce an economical machine. It appears that of great importance to the internal efficiency of a GEM is the amount of turning the air must undergo. Configurations requiring least turning of the air will undoubtedly have a great advantage, powerwise, over those requiring considerable turning.

b) Of the several methods of achieving inherent stability at the higher values of $^h/d$, considerable performance loss is associated with the radial slot method. It is not yet known how this power cost for stability compares with other methods (i.e., dual peripheral nozzle, discreet holes in base) but steps are being taken to determine the relative performance losses associated with the various known methods of stabilizing GEM's.

It is certainly premature to make firm judgements in this matter of static stability. The authors do, however, have the growing feeling that automatic stabilization devices might prove far more economical. Experiences with the 43 HP version of the P-GEM, which had servo operated control vanes, pointed up the lack of concern one may have for the usual considerations of electronic reliability. The characteristics of a GEM are such that great compromises may be made in this respect even to the extent of a complete fly-by-wire control system integrated with the automatic stabilization system. The reason for such an approach is that the hard-over signal or other control malfunction is inherently not of the same danger level as in the case of a conventional aircraft. It is felt from flight experiences that the performance loss due to automatic stabilization devices is trival compared to that loss due to the one type of aerodynamic stabilization tested.

c) It appears from analysis and flight test that the lift/momentum drag ratio as expressed by $^{L}/Dm = A\ ^{Vj}/V(1-\eta)$ is the dominant term in defining the performance envelope of any GEM. Performance envelope is here defined as the height, power, speed relationship.

d) It is interesting to note that a statically unstable GEM can be maneuvered and that the static instability appears to vanish in forward flight. This statement is qualified to include only the type of GEM which achieves its horizontal force due to tilting the lift vector. The statement is also, at this time, restricted to a circular configuration.

e) Over water operation of GEM's appears to offer certain advantages in slightly increased hovering performance and increased maneuverability by utilizing some portion or protuberance of the machine as a keel.

f) Landings and take-off are as easily accomplished from water as from land, and good confirmation has been obtained for NASA findings of a lack of an over water spray problem if jet dynamic pressures are below 5 $lbs./ft.^2$.

g) GEM operational problems over snow vary greatly with the snow surface conditions. The most serious snow problem encountered with the P-GEM has been with uncrusted snow wet enough to adhere to the surface of the machine in hovering flight. However, it has been found that even this type of snow does not seem to adhere to the machine at air speeds of approximately 25 miles per hour.

h) It is felt that much more could be learned from a few new research GEM's operating in specialized fields in order to accurately point up vital areas for further research and development. It is accordingly suggested that this be done as soon as possible to hasten the day of fully operational vehicles.

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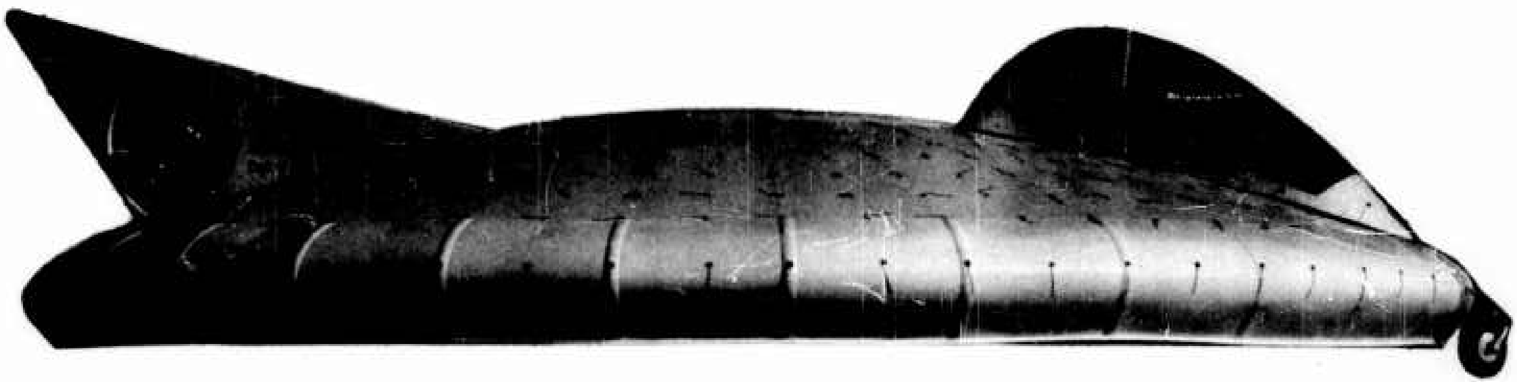
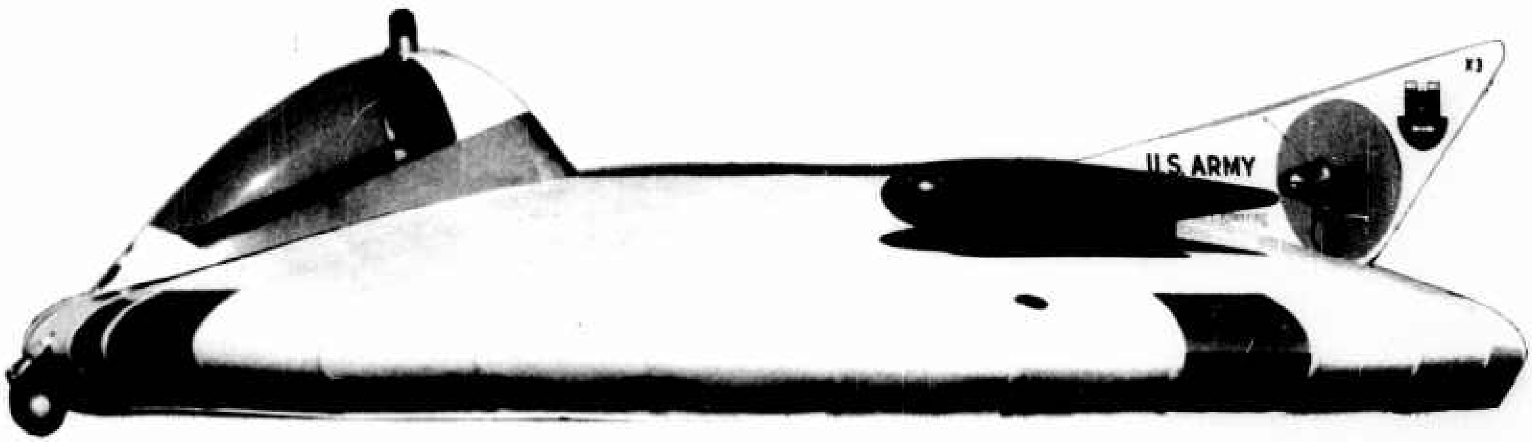
2. McNay, D.E., "Study of the Effect of Various Propeller Configurations on the Flow about the Shroud", Aero. Physics Dept. Mississippi State College, Research Report No. 14, February, 1958.



ORIGINAL CONFIGURATION



MODIFIED P-GEM

FIGURE 1

DUCT FLOW PATTERN AND INFLOW VELOCITY DISTRIBUTION
(P-GEM ~ ORIGINAL CONFIGURATION)

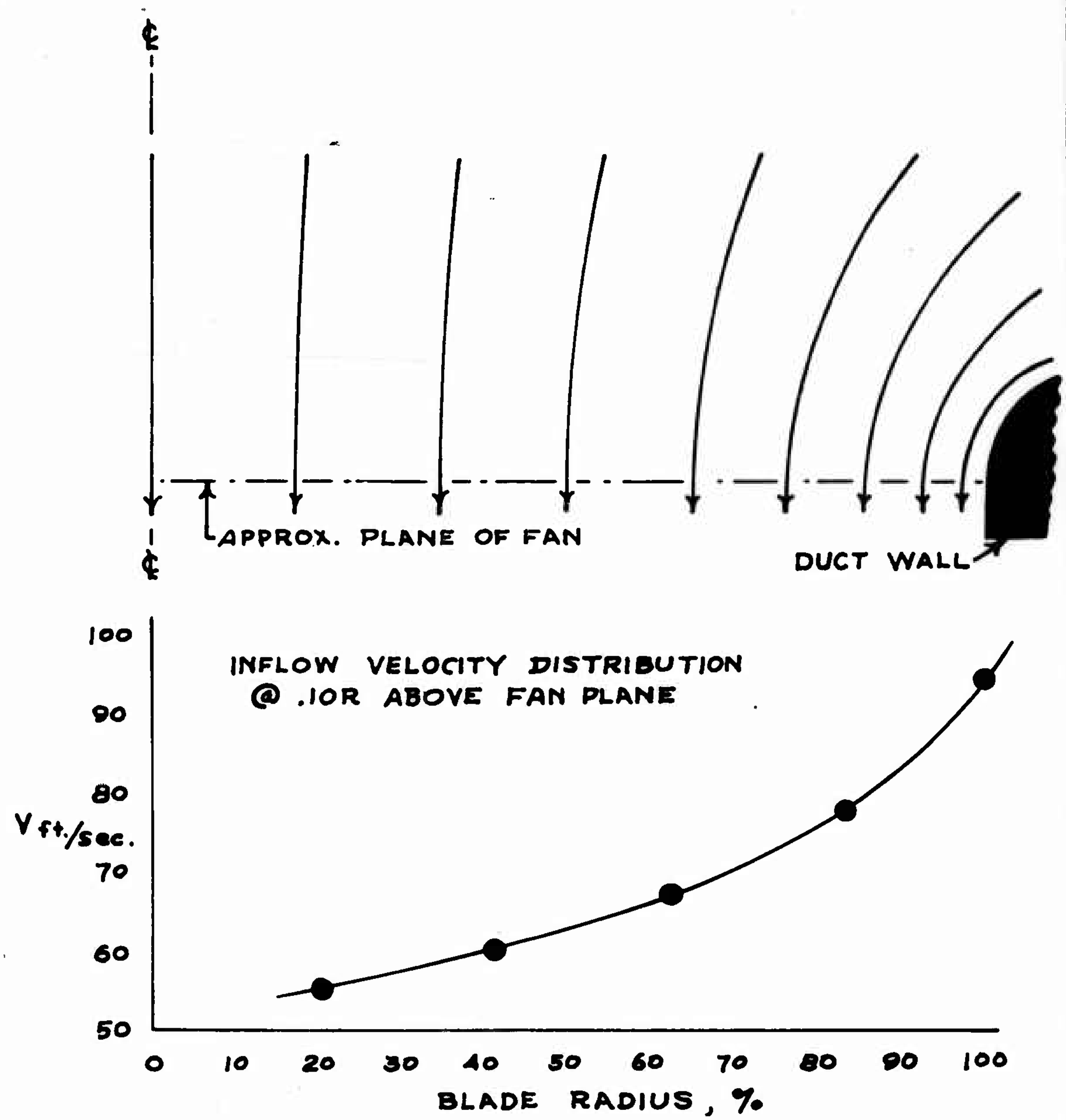
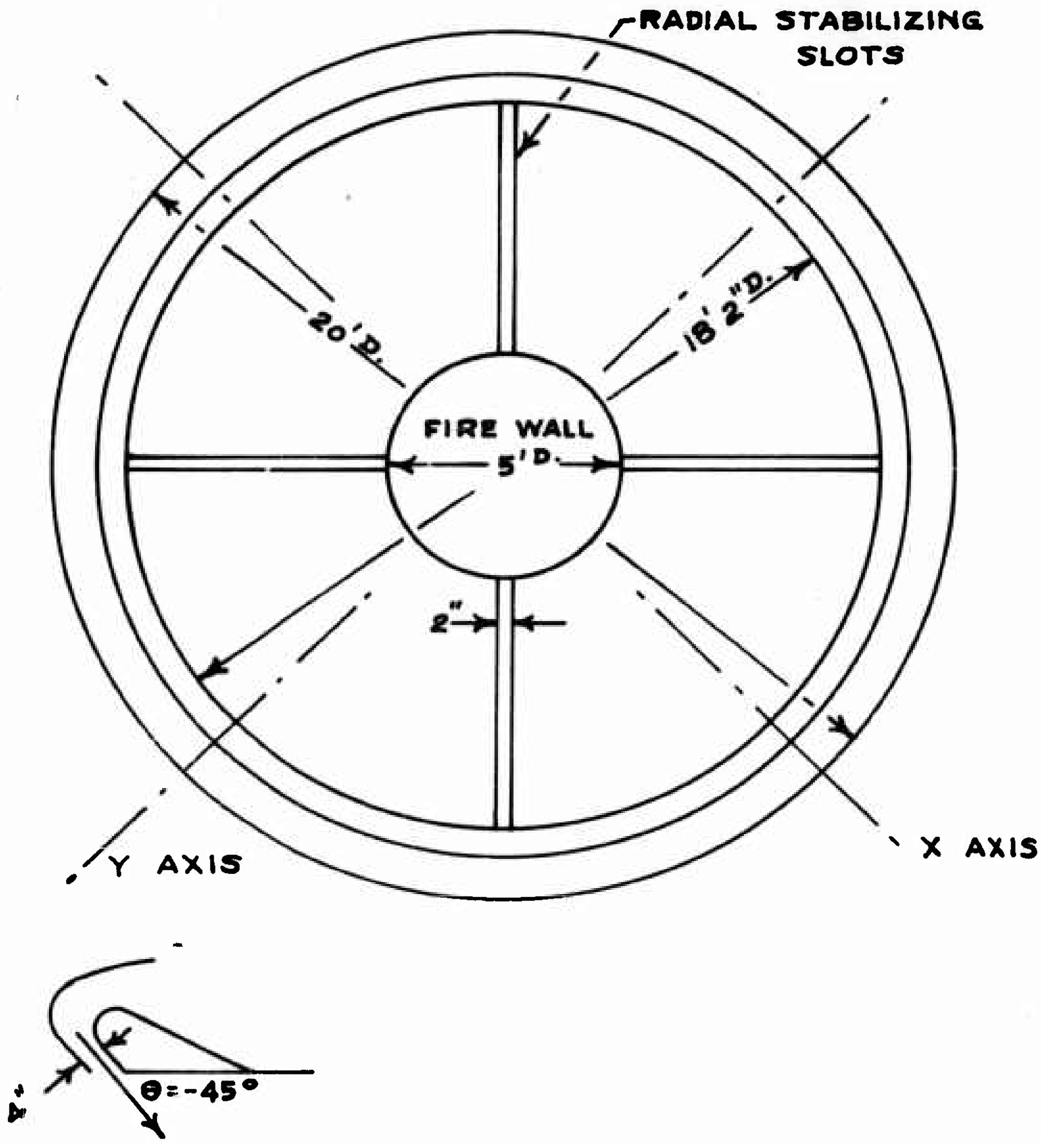


FIGURE 2



SCHEMATIC LAYOUT OF BASE
OF P-GEM

FIGURE 3

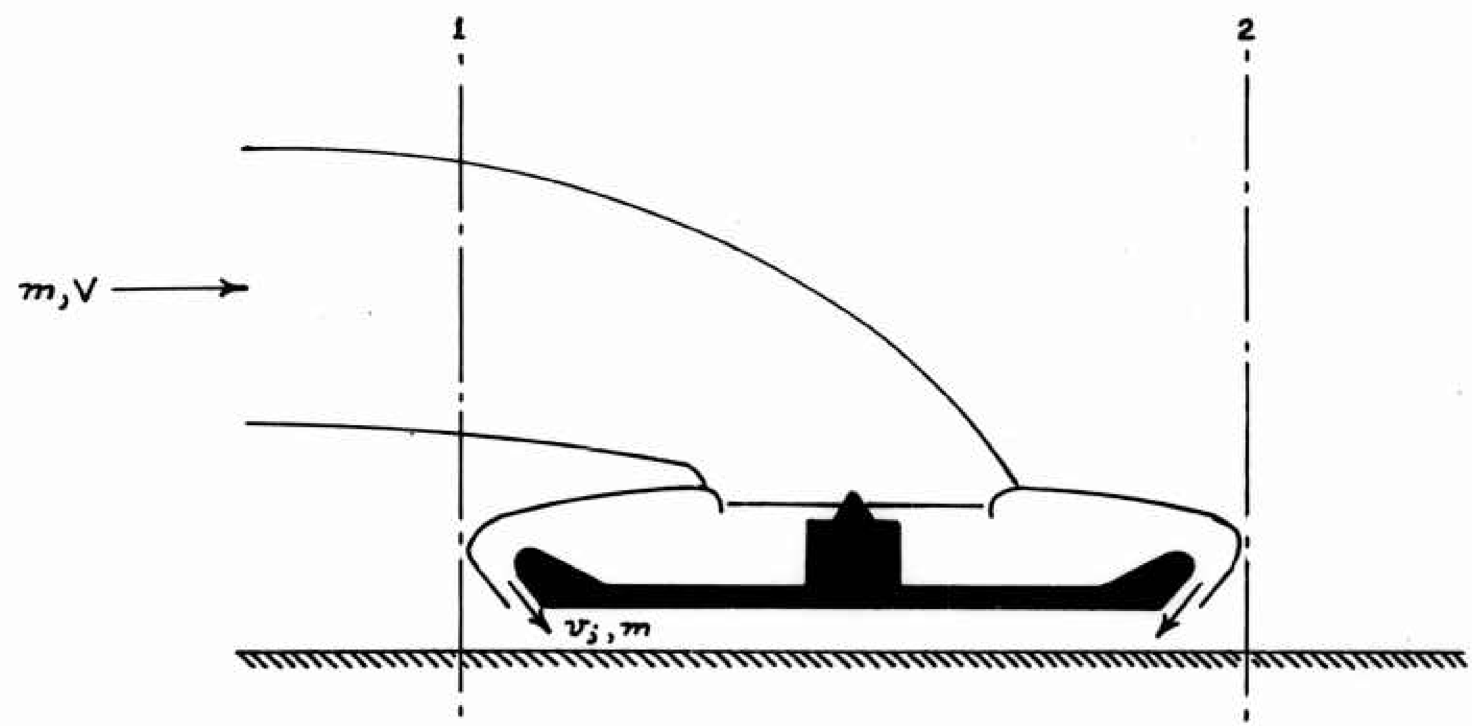


FIGURE 4

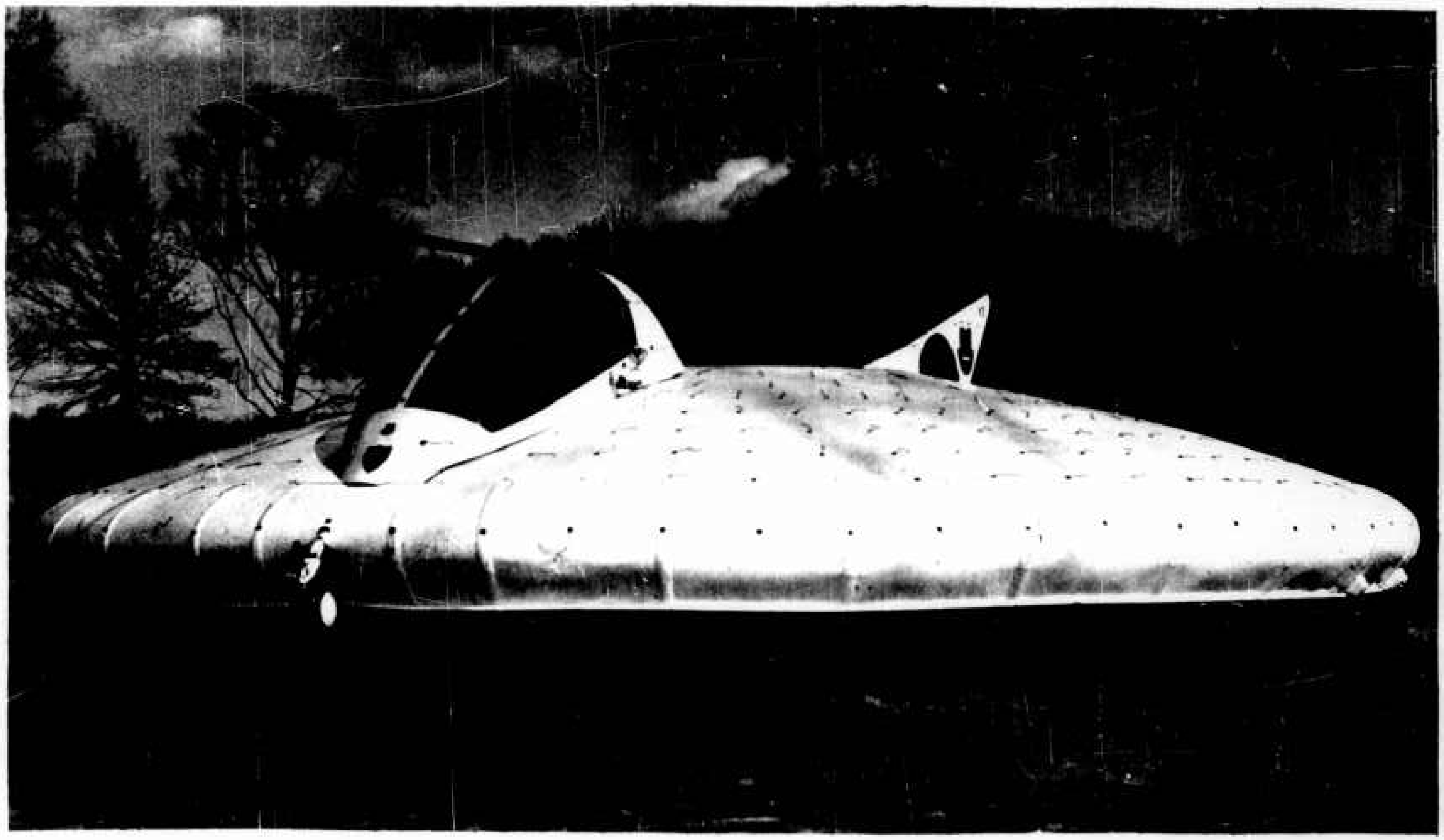


FIGURE 5

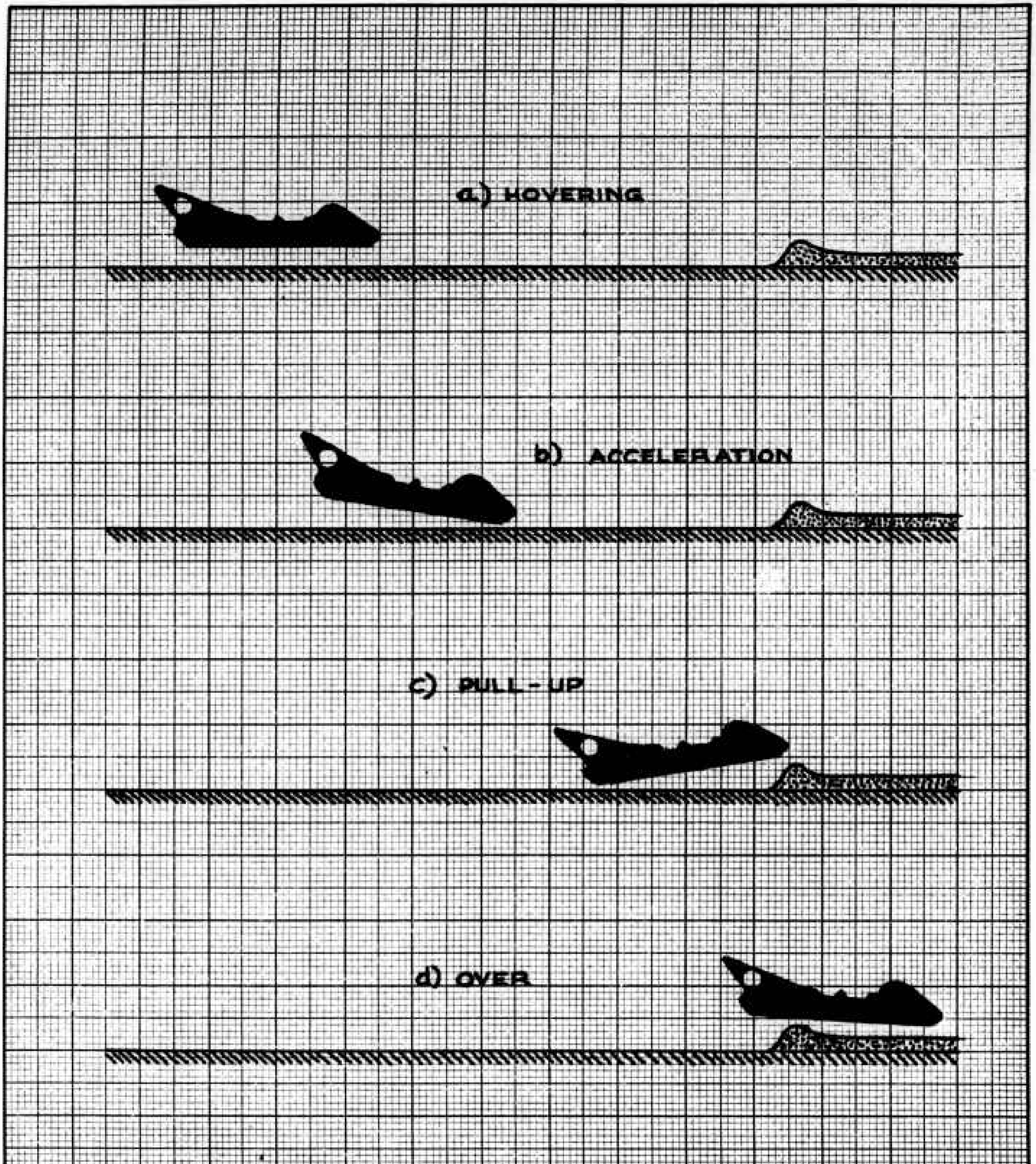


FIGURE 6

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